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Bulk density of mineral and organic soils in the Canada's arctic and sub-arctic

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ABSTRACT

Bulk density is an indicator of soil compaction subject to anthropogenic impact, essential to the interpretation of any nutrient budgets, especially to perform carbon inventories. It is so expensive to measure bulk density in arctic/sub-arctic and there are relatively very few field measurements are available. Therefore, to establish a bulk density and SOC empirical relationship in Canada's arctic and sub-arctic ecosystems, compiled all the bulk density and SOC measurements that are available in Northern Canada. In addition an attempt has been made for bulk density and SOC field measurement in Yellowknife and Lupin, to develop an empirical relationship for Canada's arctic and sub-arctic.

Relationships between bulk density (BD) and soil organic carbon (SOC) for mineral soil and organic soils (0–100 cm depth) were described by exponential functions. The best fit model, predictive bulk density (BD_p), for mineral soil, ($BD_p = 0.701 + 0.952\ \exp(-0.29\ SOC)$, $n = 702$, $R^2 = 0.99$); for organic soil ($BD_p = 0.074 + 2.632\ \exp(-0.076\ SOC)$, $n = 674$, $R^2 = 0.93$). Different soil horizons have different bulk densities and may require different predictive equations, therefore, developed predictive best fit exponential equation for both mineral and organic soils together ($BD_p = 0.071 + 1.322\ \exp(-0.071\ SOC)$, $n = 1376$, $R^2 = 0.984$), where X is a dummy variable with a value of 0 for surface peat (0–25 cm depth) and 1 for subsurface peat (25–175 cm). We recommend using the soil organic carbon density approach to estimate BD from SOC because it allows BD to be predicted without significant bias.

1. Introduction

Soil weight is referred to as soil bulk density, which is a measure of the weight (mass) of the soil per unit volume of area of land, usually given on an oven-dry (105°C to 110°C) basis, is normally expressed in $g\,cm^{-3}$. Variation in bulk density is attributable to the relative proportion and specific gravity of solid organic and inorganic particles and to the porosity of the soil. Most mineral soils have bulk densities between 1.0 and 2.0 $g\,cm^{-3}$ [1]. They also mentioned that a very compacted soil perhaps due to tractor compaction would have a bulk density of 1.4 to 1.6 $g\,cm^{-3}$ and an open friable soil with good organic matter content will have a bulk density of <1.0 $g\,cm^{-3}$. Although bulk densities are seldom measured they are very important in quantitative of soil and nutrient status of terrestrial ecosystem study [2]. Therefore, bulk

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density measurement must be known to determine the extensive soil properties (quantitative) for entire soil profile and more appropriate to local condition [3].

Bulk density of forest floor, mineral and organic, and peat soils are strongly correlated with organic carbon content [4–7]. The Canada's arctic and sub-arctic contain the largest amount of soil organic carbon storage in terrestrial ecosystems [8] but there are seldom measured soil bulk densities, which is prerequisite to calculate SOC storage. Very often SOC storage calculated by empirical relationship of SOC and bulk density that are established based on North Central United States [2]. These observations demonstrate the significant importance to establish a bulk density and SOC empirical relationship in Canada's arctic and sub-arctic ecosystems, which is our main objective to study in this manuscript. It is expensive to measure bulk density in arctic/sub-arctic and there are relatively very few field measurements are available because of the difficulties for access and limited motivations for practical used to the land for agriculture. Hence, it is very useful to compile all the bulk density and SOC measurements available in Northern Canada. In addition an attempt has been made for bulk density and SOC field measurement in Yellowknife and Lupin, Canada to develop an empirical relationship for Canada's arctic/sub-arctic.

2. Materials and methods

2.1. Site description

Measurements of soil bulk density and SOC in forest floors or mineral soils and wetlands were made in Yellowknife, NWT and Lupin, Nunavut (Fig. 1). Yellowknife situated on the north shore of Great Slave Lake at 62°27′N lat., 114°26′W long., which lies at an elevation about 180 m above sea level. The difference in elevation across the city is less than 40 m. The present day terrain consists mainly of bare rocky outcrops with glacial, river and lake sediments scattered across the area. Marshes, peat lands (bogs and fens) and small lakes occupies many of the basins and valleys. It is the largest community in the NWT and historically one of the fastest growing cities in the Canada. The ground surface has variable proportions of feathermoss, deciduous and conifer litter. The study sites were located within the almost 1000 km^2 surroundings of Yellowknife city and Lupin gold mining site is located (65°42′N lat., 111°16′W long.) 400 km northeast of Yellowknife, Nunavut, Canada (Fig. 1). In some exception of rocky part, the area is well covered with vegetation. Tree occurs on most of soils although they are rather sparse and small on many of the bog lands. The usual site for the trees are: Black spruce (*Picea mariana*) and tamarack in the swamps (peatlands), jackpine (*Pinus banksiana*) on the well drained gravel and soils, and white spruce, aspen (*Polulus tremuloides*) and some birch on the medium and fine textured soils. A variety of shrubs and other plants including dwarf birch, willow, rosebushes, labrador tea, coarse grasses and sedges occurred throughout the Yellowknife areas, while *sphagnum, lichen* and *sedges* cover *peat lands*. Black spruce (*P. mariana*) and open *peat lands* are surrounded most of the wetland and scattered jackpine (*P. banksiana*) and paper birch find footholds on bedrock outcrops.

Lupin gold mining site cover a large range of ecosystems such as grasslands and low shrubs. Flat-lying hummocks on relatively homogenous marine sediments developed in most of the areas. Ground cover is discontinuous and variable but dominated by grass species with lichens (5 to 15 cm) on top of hummocks. Many mosses and lichens are of common to frequent occurrence. Generally poor to well drained. The soils generally show weak development of surface horizons and there is little morphological evidence for horizon differentiation at most of the locations investigated. Considerable variegation was noted in the hummocks site. This is associated with poor drainage resulting from lack of lateral groundwater flow in the relatively flat-lying beach deposits. The major kind of soils development is the formation of peat and organic. The widespread prevalence of these organic soils suggests that peat has spread over lands that originally were not poorly drained. Much of the peat covers in this area is thin but in wetland areas which is really deeper. Permafrost or frozen soils were found at comparatively shallow depths (within 30 to 60 cm) in the organic soils providing the surface layer was composed of sphagnum moss. However, where sphagnum moss was absent frozen soil were seldom found with some exception.

2.2. Soil sampling and preparation

Soil samplings were random based on satellite imagery and visible differences, the results can be relying heavily on personal judgment of the soil scientist/surveyor. Worldwide, SOC in the top 1 m of soil comprises about 3/4 of the earth's terrestrial carbon; nevertheless, there is tremendous potential to sequester additional carbon in soil. From both Yellowknife and Lupin areas, all together 60 soil profiles (among these 12 are peat soils) and 173 soil horizons were identified, and horizon nomenclatures that were given based on Canadian soil classification. Pits of approximately 1 m^3 were excavated at each site; a vertical face (at least 1 by 1 m) for the site was cleared for soil sampling. Horizon thickness was measured in the pit for soil with parallel contiguous horizons. However, to analysis SOC a total of minimum three sub samples were obtained for each of the horizon and composited. Only one composite sample was used for analyses for each horizons representative SOC. Coarse fragments (>2 mm) were also included with composite sample and determined latter in the laboratory. Soil samples were then air dried in room temperature, ground (using wood block and pestle to flail type) to pass through a 2 mm sieve (63 μm for SOC determination) and samples were stored in plastic containers for further analysis. The soils examined in this study contained negligible quantities coarse fragments (>2 mm). For example, soils contained more than 15% coarse fragments, a correction factor (2.6 g cm^{-3}) were made to allow for more precise estimates of soil C density [2,9,10]. Most of the pedogenic horizons thickness examined in this study was <15 cm thick. After computing the bulk density of the corrected weight and volume, a mass-weighted mean soil density at each horizon was computed from the densities of the maximum two increments.

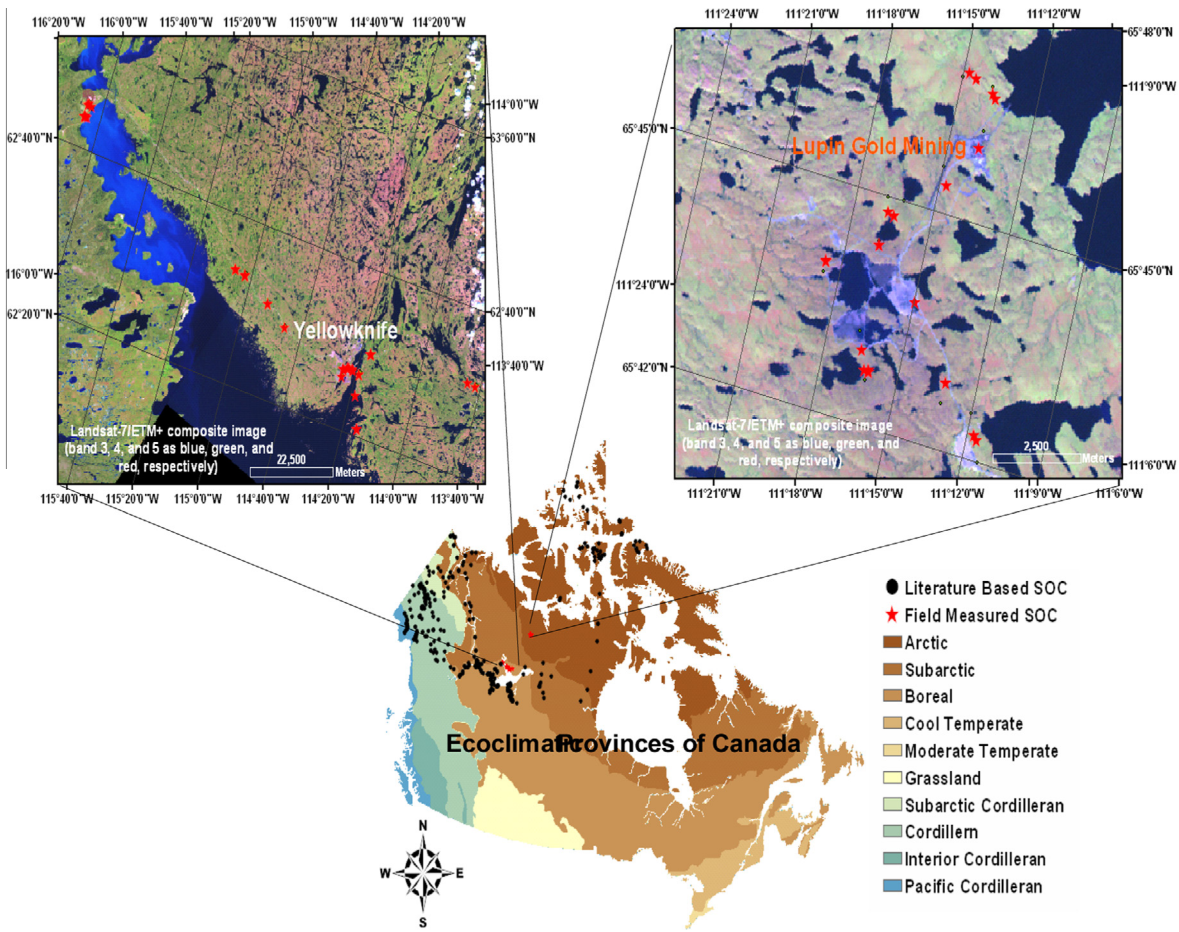

Fig. 1 – Location and distribution map of literature and field measured SOC for northern Canada.

2.3. *Soil sample collection, analysis and data calculation*

The bulk density (g cm^{-3}) measurement is necessary in order to determined on the volume of soil C. Therefore, samples were taken using the soil core method described by [11]. These were included collecting an undisturbed soil sample of a known volume (cm^{-3}) and trimming the soil to the exact volume of the cores. Precautions were taken to avoid soil compaction by ensuring that the soil inside and outside the core was the same. Care also needs to be taken to avoid compacting the soil during and after obtaining the core. Prior to sampling, 1–2 cm of the soil surface were removed to avoid plant and litter material. Using the hand hammer and block of wood, driven approximately 50 mm diameter core, beveled edge down, to a depth of core length of 3 inches (Fig. 2). The exact depth of the ring was determined for accurate measurement of soil volume. To do this, the height of the ring above the soil was measured. At least three measurements of the height (evenly spaced) were taken from the soil surface to the top of the ring and calculated the average.

Dig around the core and with the trowel underneath it; carefully lifted core out to prevent any loss of soil. Excess soil from the sample was removed with a flat bladed knife (Fig. 3).

The bottom of the core and sample was flat and even with the edges of the ring. The sample was touched as little as possible. Using the flat bladed knife, the sample was pushed out into a plastic sealable bag. Ensured the entire sample is placed in the plastic bag. Sealed and labeled the bag. The soil sample in its bag weighed and an empty plastic bag also weighed to account for the weight of the bag and soil. The soils were then oven dried at 110°C (2 to 3 days, depending on core size). Three replicate measurements were taken for

Fig. 2 – Approximately 50 mm diameter ring, beveled edge down, to a depth of 3 inches.

Fig. 3 – Excess soil was removing with a flat bladed knife from the core sample.

each of the sampling locations. Calculated soil dry bulk density following the equation below, remembering to subtract the weight of the empty core...

$$\text{Soil bulk density}(\text{g cm}^{-3}) = \frac{\text{weight of dry soil}}{\text{volume of core}}$$

$$\text{Volume of core} = \text{Pi}(3.1416)R^2 \times h$$

r = radius of core; h = the height of core

Soil carbon was determined by the combustion method using the LECO(TM) CR-412 carbon analyzer. The LECO(TM) analyses total carbon, which also includes inorganic carbon (carbonate) that was performed on loss on ignition residue in accordance with Geological Survey of Canada's sedimentology laboratory methodology. The data from the LECO(TM) was in percent organic carbon, and this was converted to kg C m^{-2}. Soil organic C pools were calculated by taking the horizon thickness or core depth interval, bulk density and percentage of SOC, and summing the values for the upper 100 cm [11]. In cases where cores or profile excavations did not match 100 cm, percentage of SOC and bulk density for the last horizon were projected 100 cm.

Soil organic C (kg C m^{-2}) for the horizon is calculated using the percent organic carbon, bulk density, and horizon thickness. The following formula is used for organic C storage:

Soil organic C storage in each horizon (kg C m^{-2}) = % organic C/100 × bulk density (g cm^{-3}) × horizon thickness (cm) × 10 (conversion factor units from g cm^{-2} to kg m^{-2}).

2.4. Data analyses

We analyzed the profile features and the spatial patterns of SOC in northern Canada based on this database. To investigate regional differences, we averaged the measurements based on terrestrial eco-zones. There are eight eco-zones in northern Canada (Canadian landmass with latitude higher than 60°N) [13]. The Arctic Cordillera eco-zone is a long strip along northeastern Canada and the database includes only four profiles in the Bylot Island (73°N, 77°W) and one profile in the very north (81.8°N, 71.3°W) for this eco-zone. Therefore, we combined this eco-zone with the Northern Arctic eco-zone in the analysis.

The profile features of the soils were analyzed based on both horizons and depth. We used four major horizons for upland soils [i.e., LFH, A (including Ah and Ae), B (including Bt, Bf, Bh, Bfh, Bm, Bmf, Bn), and C (including Ck, Cs, Cg)], and one horizon (horizon O, including Of, Om, and Oh) for peat land soils. Horizons L, F and H were combined as one horizon (LFH) because most measurements were reported this way. Some measurements did not provide the thickness of the bottom horizon, only indicating that the bottom horizon was below a certain depth. In these cases, we assumed

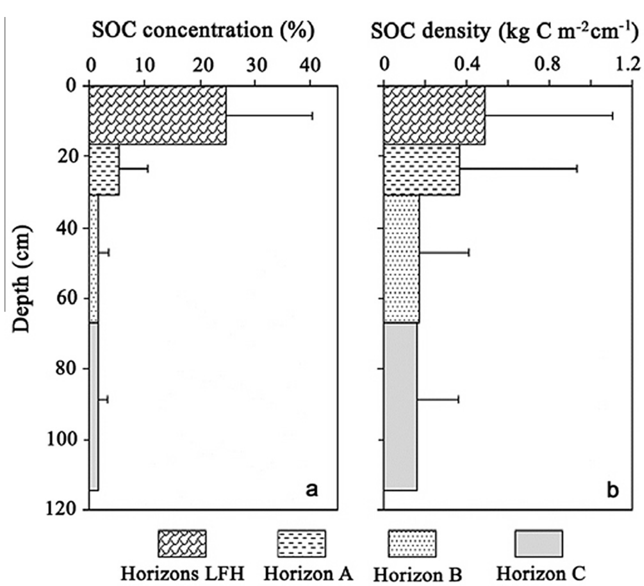

Fig. 4 – The mean distributions of SOC with horizons in upland soils in northern Canada. (a) SOC concentration, and (b) SOC density calculated as the total SOC content in each horizon divided by its thickness. The horizontal bars are standard deviations.

their thickness as 20 cm. In addition to the distribution of SOC with horizons, we also calculated the distribution of SOC with depth for each 10-cm layer from the surface to 1-m depth. We used 1-m depth for this calculation since it is often used in several studies because SOC in the top 1 m of soil comprises about ¾ of the earth's terrestrial carbon [11,12,14] and only a few mineral soil profiles included measurements deeper than 1 m. If the measured depth is less than 1 m, the SOC concentration (percentage) and SOC content (kg C m^{-2}) were calculated to the maximum measurement depth without extrapolation. If a 10 cm soil layer includes two or more horizons, the mean SOC concentration of this layer was calculated as the weighted average based on the thickness of the horizons in this 10 cm layer.

3. Results and discussion

3.1. *The distribution of SOC with soil horizons*

The average SOC content of four different soil horizons averaged for all the upland sites measured in northern Canada (Fig. 4). The mean thicknesses are 16.4, 14.6, 35.8 and 47.6 cm for horizons LFH, A, B, and C, respectively. The concentration of SOC in the organic layer (horizons LFH) is much higher than in mineral soil horizons. SOC concentration in horizon A is higher than in horizons B and C, while the SOC concentration in horizon C is almost the same as in horizon B (Fig. 4a). The SOC density, in kg C m^{-2} cm^{-1}, is not as different as that of the SOC concentration among horizons due to the increase in bulk density with depth (Fig. 4b). Because horizon C is thicker than horizons A and B, the total SOC content in horizon C (7.4 kg C m^{-2}) is much higher than in horizons A (5.2 kg C m^{-2}) and B (5.9 kg C m^{-2}), and is close to the SOC content in horizons LFH (7.9 kg C m^{-2}). The total SOC content of the whole profile averaged for all the upland soils is 26.4 kg C m^{-2}.

The distribution of soil horizons and their SOC conditions are different among eco-zones. On an average for the upland soils, the soil profiles are thicker in Southern Arctic, Boreal Plain, and Taiga Shield than in other ecozones (Fig. 5a). Most of the measured sites in the Boreal Plain ecozone were located in a small northern portion of the ecozone, therefore, our results may not represent this ecozone as a whole. The soil in Boreal Plain is deep because all of the soil horizons (hori-

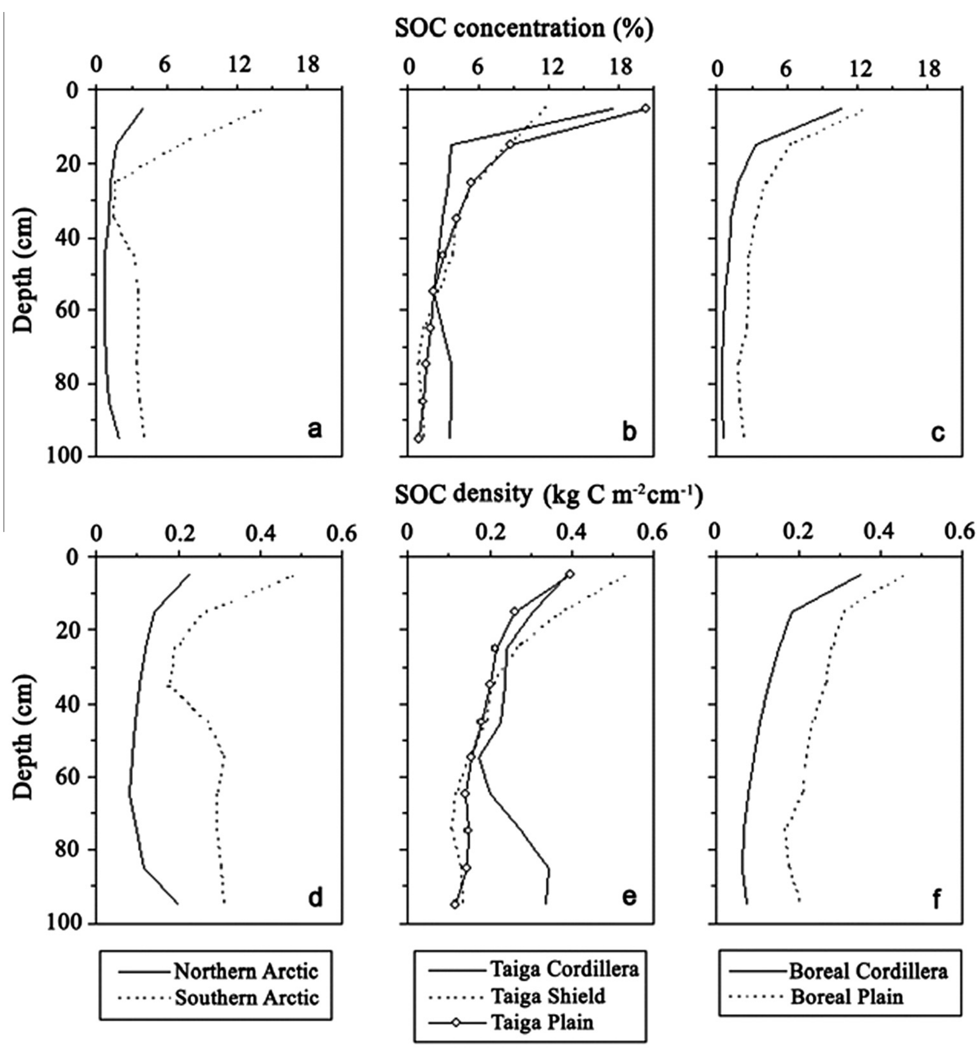

Fig. 5 – The distribution of SOC concentration (a–c) and SOC density (d–f) in the top 100-cm soil profile averaged for each eco-zone in northern Canada.

zons LFH, A, B, and C) are relatively thick, especially the LFH horizons. But the thickness of the soil profile in the Southern Arctic is due mainly to the depth of the mineral horizons (horizons A, B and C). Almost all the soil horizons in the Taiga Cordillera ecozone are thinner than in other ecozones, especially the organic layer, probably due to its mountainous conditions. The average SOC concentration of the whole soil profile (the average weighted by the thickness of the horizons shown on the right side of the histogram in Fig. 5b) is higher in the Taiga and Boreal Plains, where the wet conditions of the Mackenzie Valley favor the accumulation of organic carbon in soils. The total SOC content (kg C m^{-2}) in soil profiles is higher in the Southern Arctic and Boreal Plain ecozones than in other ecozones (Fig. 5), and the differences among ecozones are related more to the differences in horizon thickness than in SOC concentration. The average SOC content calculated for the Taiga Plain eco- zone was not as high as mapped [14] because the average in this study was only for upland soils. Peatlands are widespread in this region [15] and most of the SOC is stored in peatlands. For peat soils in the database, the average depth of the peat measured is 61.3 cm and the average SOC content is 39.8 kg C m^{-2}. These values are much less than the averages from the SOC spatial database of Canada [14] [the average depth and SOC content of bogs and fens in northern Canada (>60°N latitude) are 178.3 cm and 124.6 kg C m^{-2}, respectively) because not all the measurements in our database reached the bottom of the peat. The mean SOC concentration of the O horizons is 38.2%, which is slightly higher than the average SOC concentration of bogs and fens in northern Canada (33.4%) calculated from the spatial database of [14].

3.2. *The distribution of SOC with depth*

Fig. 5(a, b and c) shows the distribution of SOC concentration with depth averaged for each eco-zone. The SOC concentration decreases with depth in the top 50 cm soil in all the eco-zones with much of the change occurring in the top 20 cm. Below 50 cm, however, SOC concentrations differ very little or increase with depth for some eco-zones. The average SOC concentration in the Northern Arctic eco-zone in the top 50 cm of the profile is significantly lower than in other eco-zones because of its extremely cold conditions. The SOC concentration in the top 50 cm of the profile is high in the Boreal Plain, Taiga Plain and Taiga Shield. The Southern Arctic eco-zone shows a sharp decrease in SOC concentration from the top 10 cm layer to 10 to 50 cm layers. Below the depth of 50 cm, SOC concentration does not change much, or even increases with depth in six of the 20 profiles measured in this eco-zone.

The SOC density (kg C m^{-2} cm^{-1}) decreases with depth in the top 50 cm soil layers, but the decrease is not as sharp as the decrease in SOC concentration, because soil bulk density is usually higher in deeper layers (Fig. 5d, e, and f). In 50 to 100 cm layers, the average SOC density decreases slightly with depth in five eco-zones, but increases with depth in the remaining two eco-zones (Taiga Cordillera and Norther Arctic). The SOC content in the 50 to 100 cm layer is almost as much as in the top 50 cm layer in Northern Arctic, Southern Arctic and Taiga Cordillera eco-zones. Averaged over all profiles in northern Canada, the SOC content was 11.6 kg C m^{-2} in the top 50 cm soil layer, and 7.7 kg C m^{-2} in the 50 to 100 cm layer; the latter being 40% of the total SOC in the top 100 cm of soils.

3.3. *Relationships of field measured and literature based bulk density and SOC content*

Soil carbon stocks are not only depend on soil carbon concentrations but also depend on soil bulk density which indicates a very strong relationship between soil carbon stock and bulk density (Fig. 6). Most studies measured horizon thickness in

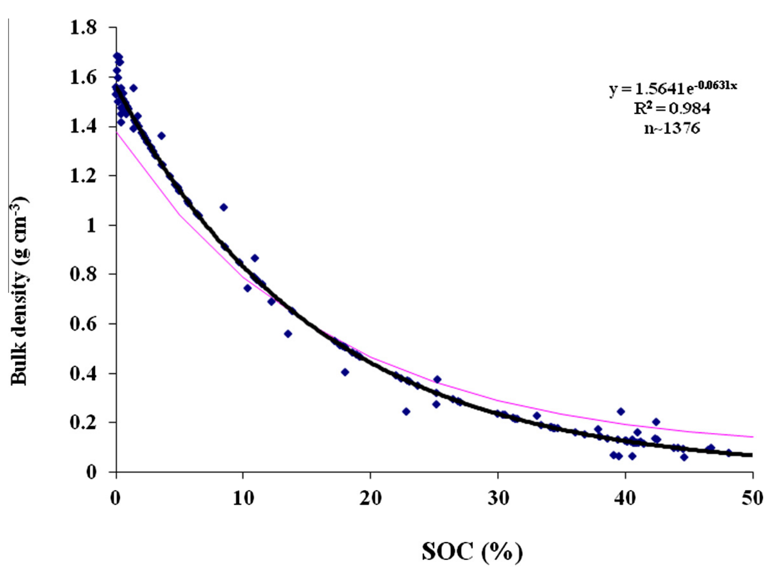

Fig. 6 – Best fit relationship between bulk density and soil organic carbon concentrations for mineral (0–25 cm) and organic soils (25–100 cm) across Canada's arctic and subarctic. The best fit model, predicted bulk density (BD_p), for mineral soil (BD_p = 0.701 + 0.952 exp(−0.29 SOC), *n* = 702, R^2 = 0.99); for organic soil (BD_p = 0.074 + 2.632 exp(−0.076 SOC), *n* = 674, R^2 = 0.93); and for both mineral and organic soil (BD_p = 0.071 + 1.322 exp(−0.071 SOC), *n* = 1376, R^2 = 0.984).

the soil profile with parallel and contiguous horizons in our literature based SOC. In accordance with a soil profile study, there is various depth and horizon nomenclatures that were also identified based on the Canadian System of Soil Classification [15]. Due to a large variation in soil horizon thickness and horizon notation with more than 1376 points, the literature depth of soil profiles was reorganized based on major soil horizon name. Our primary goal of the complete database was to allow estimation of SOC content of a soil profile. Therefore, the calculation was required for each horizon thickness, bulk density, and mass percentage of organic carbon in the soil profile. The bulk density of organic, inorganic and peat soil is related to organic matter content [5,16,17]. However, the collection and analysis of bulk density samples were inconsistent among soil surveyors, and only a small portion of the horizons described measured bulk densities in literature based SOC data set. In lieu of measured bulk densities, an empirical relationship between SOC content and bulk density has been used to estimate soil bulk density. Numerous published equations have explored this relationship [18,5,2]. If there was no measurement, we could estimated soil bulk density based on its organic content, although it was based on the North Central United States [2] but it is the latest.

$$\mathrm{BD} = 0.075 + 1.301\exp(-0.06\,LOI) \quad \text{(for mineral soils)}$$

$$\mathrm{BD} = 0.043X + 4.258\exp(-0.047\,LOI) \quad \text{(for organic\&peat)}$$

where, BD is bulk density ($\mathrm{g\,cm^{-3}}$), LOI is loss of ignition in percentage or percentage of organic matter content. X is a dummy variable with a value of 0 for surface peat (0–25 cm depth) and 1 for subsurface peat (deeper than 25 cm).

To better reflect the soil conditions in a user's area of interest (such as Canada's north), it may be desirable to recalculate the estimated bulk densities using knowledge of local conditions and the current field estimated values would give a good base line reference for further research. Therefore, we have collected site specific samples (50 soil horizons from 16 soil profiles) for bulk density analysis and following a regression analysis there is very strong relationship ($R^2 = 0.984$) found between measured SOC and bulk density (Fig. 6). We also superimposed our empirical relationship equation [2] on field measured equation. This data indicate in our literature based SOC data, where no soil bulk density measurement was available, we have overestimated bulk density for peat and organic soils and under estimated for mineral soils. These give significant differences of SOC stock measurement which attributes in our literature and field measured database [10,19]. In addition variation in horizon thickness also can lead to substantial differences in computed bulk density, is suggesting site specific bulk density analysis, which is really essential to calculate more reliable SOC stock in Canada's north rather than the use of North Central United States [2]. Although there are very few field measured SOC data is available in compare to a huge area for northern Canada to establish a valid empirical relationship between SOC content and bulk density. Therefore, to provide a good representation about the current field measured relationship between SOC and bulk density, more site specific field measurements are emphasized for Canada's north [10]. Hence, to establish a valid empirical relationship for Canada's arctic and sub-arctic SOC stock measurements could be possible using field measured SOC content and bulk density measurements.

4. Conclusion

Equations have been developed for predicting bulk densities of soils. A strong relationship between organic carbon content and soil bulk density is utilized to develop equation for predicting the bulk densities of mineral and organic soil in Canada's arctic and sub-arctic. Different soil horizons have different bulk densities and may require different predictive equations, therefore, developed predictive best fit exponential equation for both mineral and organic soils together. Hence, a quantitative relationship allowing bulk density to be estimated from bulk sample properties would be very useful as organic matter plays a dominant role in the bulk density of the soil because of its much lower density than mineral particles and its aggregation effect on soil structure. Generally, the higher the organic matter the lower the bulk density. Estimates of bulk density on specific soils have been made from organic matter concentrations using regression equations. However, in estimating bulk densities from organic matter content, particularly when applied to soils and environments different than the ones in which the original coefficients were calibrated. This technique would only be useful for looking at general trends among soils and would not be appropriate for evaluating the effects of soil disturbance on compaction as soil horizons compacted by mechanized disturbance are likely to be more denser than computed from these equations.

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